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Author(s)	Deng, Pengru; Kuwagaki, Junya; Matsumoto, Takashi
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Flexural fatigue behavior of Ultra-High Performance Fiber Reinforced Concrete

Pengru Deng^{1*}, Junya Kuwagaki² and Takashi Matsumoto³

¹Professor, National Engineering Research Center of High-speed Railway Construction Technology, Central South University, Changsha 410075, China; Email: pengrudeng@csu.edu.cn

²Graduate student, Graduate School of Engineering, Hokkaido University, Hokkaido 060-8628, Japan;

³Professor, Faculty of Engineering, Hokkaido University, Hokkaido 060-8628, Japan; Email: takashim@eng.hokudai.ac.jp

*Corresponding author

ABSTRACT

Even though UHPFRC has been extensively utilized in infrastructures owing to its excellent mechanical properties, its fatigue behavior remains unclear because related research is very limited. In this study, the fatigue characteristics of UHPFRC were investigated using a four-point bending experiment. In this study, the fatigue characteristics of UHPFRC were investigated using a four-point bending experiment. To determine the fatigue load conditions, static tests were conducted at different loading speeds and ages before, during, and after the fatigue tests. The obtained mechanical properties exhibited a clear dependence on loading rate and age duration. Consequently, a loading frequency of 3 Hz, which is close to that experienced in real infrastructures, was employed in the fatigue tests. A linear S-N relation with a 0.87 fatigue endurance limit was obtained on a semi-logarithmic scale. Additionally, the fatigue life showed a close relationship with the initial cycle deformation. Correspondingly, threshold values of deformation indicators were proposed for predicting the occurrence of fatigue failure. Furthermore, a linear positive relationship was found between the density of multiple fine cracks and fatigue life, based on post-fatigue crack measurements using a microscope. The relatively narrow crack width compared to other cementitious composites demonstrated UHPFRC's superior resistance to corrosion factors. Consistent with the linear S-N relation, the structural degradation appears to be governed by a fiber slippage-to-pull mechanism, as no fiber rupture was observed.

KEYWORDS

UHPFRC; fatigue; flexure; steel fibers; multiple cracking;

1 INTRODUCTION

Under uniaxial tension, ultra-high performance fiber reinforced concrete (UHPFRC) exhibits a high strength (>10 MPa) and a three-stage (elastic, strain hardening, and strain softening) ductile behavior owing to a relatively large proportion of steel fibers. Besides, a self-compacting characteristic associated with excellent flowability makes UHPFRC very suitable for repairing structures. In addition, attributing mainly to the super dense matrix, the UHPFRC is impermeable even under high tensile strains up to about 1.3% (Charron et al., 2007). Hence, UHPFRC is a highly calibrated composite especially suitable for structural rehabilitation. It can act as a protective coat preventing the penetration of detrimental environmental elements to a great extent together with improving structural performance.

In practical applications, UHPFRC was normally designed as a thin layer to achieve an economic construction, and in the meantime to minimize the possible detrimental effects of the spatial variance of the material properties induced by the disperse of the steel fibers. In Japan, a 20-30 mm thickness is commonly employed in the rehabilitation of existing bridge RC or orthotropic steel decks (Manabe et al., 2018; Kosaka, 2020; Koda et al., 2013). It was reported that a thin layer of UHPFRC on the top or bottom surface of reinforced concrete (RC) beams can effectively improve the static flexural strength and durability by improving the structural stiffness and delaying the damage localization (Brühwiler and Denarié, 2013; Safdar et al., 2016). Deng et al. (2020) also validated the fatigue performance enhancement owing to a 25 mm thickness of UHPFRC overlaid locally on a partly damaged RC slab experimentally and numerically. In terms of the applications on steel bridge decks, Deng et al. (2022), Ma et al. (2021) and Ma et al. (2023) investigated the static and fatigue performance of OSDs strengthened with a UHPFRC overlay, where the stress reduction and fatigue life extension effects of a 25 mm thin UHPFRC were validated quantitatively.

The exiting researches demonstrate that covering UHPFRC should be promising in infrastructure rehabilitation. In fact, it has been widely exploited in engineering projects. Nevertheless, research on the material fatigue performance is limited as listed in **Table 1**. Makita and Brühwiler (2014) performed uniaxial tensile fatigue tests on UHPFRC with a dimension of $750 \times 150 \times 40$ mm³ under a 10 Hz loading frequency, where the specimens were loaded statically up to elastic, strain hardening, or strain softening domains, respectively, before the fatigue loading. In the fatigue results, a significant scatter was observed. This may partly be attributed to the employed testing method as the uniaxial tension is difficult to be ensured especially after cracking. Circumventing the uniaxial tensile tests, three-point fatigue flexural tests have been carried out on two kinds of typical UHPFRCs, i.e. Ductal and CERACEM. Behloul et al. (2005) concluded that UHPFRC is safe for fatigue design as scarce damage was observed after one million cycles on all specimens, whereas only one combination of fatigue loading range was

applied and the upper limit was still in the elastic domain. Farhat et al. (2007) performed the tests on two dimensions of specimens, i.e. $360 \times 90 \times 35 \text{ mm}^3$ and $500 \times 100 \times 100 \text{ mm}^3$ under several load ranges with the upper limit varying from 70% to 90% of the ultimate flexural strength, where an approximate 85% endurance limit was concluded for the smaller specimens. It was reported that the scatter of the results became much more predominant in larger specimens. Besides, it is interesting to notice that the thickness is the primary difference between these two types of specimens. A four-point fatigue bending was performed on UHPFRC beams with dimensions $1000 \times 125 \times 125 \text{ mm}^3$ and $600 \times 200 \times 40 \text{ mm}^3$ by Chanvillard et al. (2004) and Parant et al. (2007). Parant et al. (2007) concluded that fatigue failure never appears for a loading ratio lower than 0.65 based on experimental results under a 2.5 Hz of loading frequency. It was suggested that efforts should be put into developing appropriate production techniques to reduce variance among specimens as well as control construction quality.

Table 1 Review of tensile and flexural tests on UHPFRC

Reference	Before fatigue test	Method	V_f (%)	Specimen dimensions	Run-out cycles	Endurance limit	Remark
Makita and Brühwiler (2014)	Without preload	DTT	3.0	$750 \times 150 \times 40 \text{ mm}^3$	10 million	$0.7f_{Ute}$ $0.61f_{Utu}$	-
	Preloaded into strain-hardening domain					$0.6f_{Ute}$ $0.52f_{Utu}$	-
	Preloaded into softening domain					$0.45f_{Ute}$ $0.39f_{Utu}$	-
Farhat et al. (2007)	Without preload	3PBT	6.0	$360 \times 90 \times 35 \text{ mm}^3$	1 million	$\sim 0.85f_{Ube}$	-
	Without preload		6.0	$500 \times 100 \times 100 \text{ mm}^3$		N/A	High scatter
Chanvillard et al. (2004)	Preload to 0.3 mm crack opening	3PBT	2.0	$400 \times 100 \times 100 \text{ mm}^3$	1 million	$0.54f_{Ubu}$	-
Lappa et al. (2006)	Without preload	4PBT	2.5	$1000 \times 125 \times 125 \text{ mm}^3$	2 million	N/A	High scatter
Parant et al. (2007)	Without preload	4PBT	11.0	$600 \times 500 \times 40 \text{ mm}^3$	2 million	$\sim 0.82f_{Ubu}$	No failure below $0.65f_{Ubu}$

*Note:

DTT: direct tension test;

3PBT: 3-point bending test;

4PBT: 4-point bending test;

f_{Ute} : tensile elastic limit based on DTT;

f_{Utu} : tensile strength based on DTT;

f_{Ube} : flexural elastic limit based on bending test;

f_{Ubu} : flexural strength based on bending tests.

The preceding literature review reveals several problems which have not been properly addressed. Firstly, instead of fatigue behaviors including a conventional stress-life relation, the existing research only proposed fatigue endurance limits. Secondly, the dimensions of the used specimens were quite different from real engineering applications, whereas it was reported that the mechanical behaviors of UHPFRC is greatly dependent on the specimen dimensions which affect the dispersing characteristics of steel fibers (Zhou and Uchida, 2017a, 2017b). Al-Azzawi and Karihaloo (2017) found that the fatigue endurance limit may be decreased from more than 0.8 to approximately 0.64 if the fiber distribution becomes nonuniform. Hence, to provide a

relatively trustworthy reference, the tested specimens should be designed to have an approximate dimension to the target engineering applications. In addition, referring to fatigue tests on other cementitious composites, a high loading frequency was normally employed in the existing fatigue tests. Nevertheless, the UHPFRC which is deformable and strong should be more sensitive to loading rate. The applicability of the loading frequency remains in doubt. Moreover, damages were normally introduced into the specimens by static pre-loading tests. As a result, the reference value of the achieved fatigue characteristics may be limited. Furthermore, even though not very obvious, it seems that the easier-to-implement bending load provides less variance than the uniaxial tensile load, nevertheless, comprehensive fatigue bending tests on UHPFRC is still not available (Farhat et al., 2007; Makita and Brühwiler, 2014).

Therefore, this study aims to propose an S-N relation of UHPFRC as well as investigate the material fatigue flexural characteristics by implementing four-point fatigue flexural tests on UHPFRC beams. The beam specimens were shaped to have a thickness approximate to that commonly used in practical structural rehabilitations to mitigate influence of geometric dimensions. As a preparation, static flexural tests were conducted under different loading speeds and at different ages for determining the fatigue loading conditions as well as evaluating the corresponding effects. The fatigue flexural loading is then applied on a total of 28 UHPFRC beams under four loading levels. The deformation behaviors, cracking manners, and failure patterns were presented and interpreted by exploiting measurements, such as deflection, strain, and crack width. Based on these experimental observations, the fracture process and deterioration mechanisms were discussed and elucidated. Especially, even though the result variance due to UHPFRC's inherence is observed, a close and definite relationship between the behaviors in the initial loading cycle and fatigue endurance of each specimen is identified, which can provide references for the structural design.

2 SPECIMEN PREPARATIONS

In this study, two shapes of specimens, i.e. a cylinder specimen with a 50 mm diameter and a 100 mm depth and a beam specimen with a dimension of $240 \times 60 \times 25 \text{ mm}^3$, were prepared for the compression and flexural tests, respectively. The 25 mm thickness was employed as it is normally used in bridge deck repairing.

The employed UHPFRC mix is composed of ingredients including steel fiber, steel wool, fine aggregates, cement and a mixture specifically designed. The mix is characterized by an about 0.25 water-to-cement ratio and a 4 vol.% of straight steel fibers with a length of 13 mm and a diameter of 0.16 mm. The flowability of the fresh state of UHPFRC was evaluated by standard flow-cone tests based on the JIS standard (2015). The exploited two consecutive batches of material exhibited similar flow

spread diameters of about 290 mm as shown in **Fig. 1**. The room temperature and temperature of the used water were 24.5°C and 24°C, respectively, and the relative humidity was measured to be 79%. The specimens were fabricated in a sequence of casting in mold, spraying water to relieve shrinkage, covering with a plastic sheet to avoid water evaporation, demolding at approximately 24 hours, and moving into 20°C of water for curing until the testing day. To minimize the variance due to casting, the fresh state of UHPFRC was always poured from the center of all the beam specimen molds.

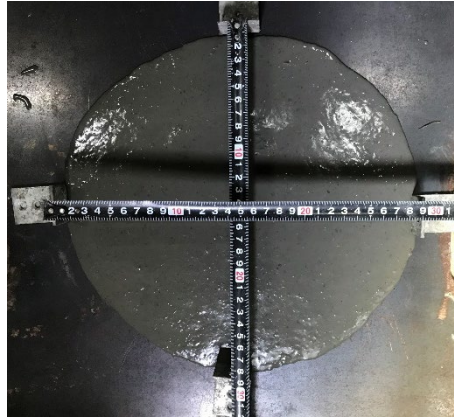


Fig. 1 Flow-cone test result

Prior to each test, the unevenness of the top surface of the cylinder specimens was removed with a grinder. As for the beam specimens, to minimize the variance, a specimen selection procedure was proposed using the specimens' density which may reflect the content of the steel fibers. The detailed procedure is given as follows. Step 1: 100 specimens were prepared using the same dimension of molds; Step 2: the dimensions and weight of each specimen were measured after demolding. Afterward, the density was calculated using the measurements; Step 3: the distribution of the numbers of specimens against their densities was drawn as shown in **Fig. 2**. Correspondingly, the mean value and mean value and standard deviation of the UHPFRC density for the 100 specimens are calculated to be 2.498 tons/m³ and 0.0366 tons/m³, respectively. Besides, it is found that the obtained data basically follows a normal distribution; Step 4: the average density of all specimen and the absolute difference of each specimen away from the average density were calculated. Then, the specimens for the static tests were selected in an order of the absolute difference from the smallest to largest; Step 5: the specimens for the fatigue tests were chosen from the rest of the middle three column ones by random draws.

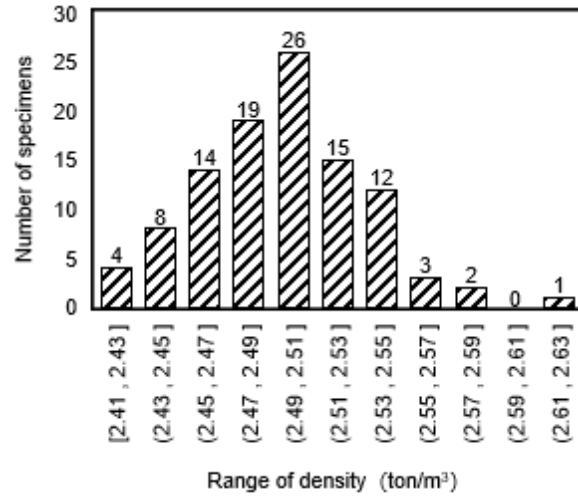


Fig. 2 Distribution of specimen density

3 STATIC TESTS AND RESULT DISCUSSIONS

In this study, quasi-static compressive and four-point flexural tests were conducted at 28 days before the fatigue tests to obtain the static compressive and flexural properties. Considering that the fatigue tests will last for a long period, the quasi-static compressive and flexural tests were conducted during and after the fatigue tests on 90 days and 165 days, respectively. The overall schedule of all tests is listed in **Table 2**. Besides, as the flexural behaviors of UHPFRC may be influenced by the strain rate and loading frequency, flexural tests under two other loading speeds were conducted as well prior to the fatigue tests. Finally, jointly referencing the experimental results of the flexural tests under the three loading speeds, the fatigue loading frequency was determined and the fatigue stress levels were calculated.

Table 2 Schedule of all tests

Age (days)	Loading conditions			Remarks
	Compression	Static flexural	Fatigue flexural	
28	0.25 MPa/sec	0.1 mm/min	-	Quasi-static
29-42	-	-	10 Hz	Stopped considering strain stiffening effect
45	-	400 mm/min	-	Corresponding to 20 Hz
48	-	60mm/min	-	Corresponding to 3 Hz
49-91	-	-	3 Hz	Approximate to practical
90-93	0.25 MPa/sec	0.1 mm/min	-	Quasi-static
95-160	-	-	3 Hz	Approximate to practical
165-166	0.25 MPa/sec	0.1 mm/min	-	Quasi-static
172-200	-	-	3 Hz	Load modified considering strength development

3.1 Compressive tests

Quasi-static compressive tests were performed using a feedback-controlled loading machine in accordance with the JIS standard (2017) under a load-controlled condition. The load speed was 0.25 MPa/sec for the three different ages. Under each condition, the static compressive properties of UHPFRC were determined by averaging the results of the three specimens. As

shown in **Fig. 3**, to measure the material compressive behaviors as well as the Poisson's ratio, two 30 mm strain gauges along the vertical and hoop directions were attached at the mid-depth of the specimens on two opposite sides of each specimen.

3.2 Four-point flexural tests

Employing a 100 kN capacity feedback-controlled loading machine, four-point quasi-static flexural tests were also conducted as shown in **Fig. 4**. Correspondingly, the pure bending and shear spans were 60 mm. The quasi-static flexural tests were also conducted on the three ages. All the quasi-static flexural tests were performed under displacement control at a constant rate of 0.1 mm/min in accordance with the JCI standard (2007) for the test method of fiber-reinforced concrete. As for the two extra flexural tests, 400 mm/min and 60 mm/min were calculated as these two loading speeds are corresponding to a 20 Hz loading frequency which is just over the upper limit of the loading frequency acceptable for fatigue tests on cementitious materials (Medeiros et al., 2015) and a 3 Hz loading frequency which is approximate to the normal loading frequency on real infrastructures, respectively. Both groups of flexural tests were conducted at 45 days. Five specimens were exploited for each condition as it was reported that a significant variance may exist in the flexural properties of UHPFRC.

As shown in **Fig. 4**, two laser displacement meters were set above both supports to obtain the rigid movement and another two laser displacement meters were mounted on both sides of specimens at midspan. Thus, the deflection evolution induced only by the specimen deformation could be measured. The laser displacement meters are featured an accuracy of $\pm 0.1\%$ mm across the entire range of linearity and a repeatability of 2 μ m. Two 30 mm strain gauges were attached on the top surface of the specimens at midspan to measure the compressive strain, and one 30 mm strain gauge was exploited to the tensile strain on the bottom surface.

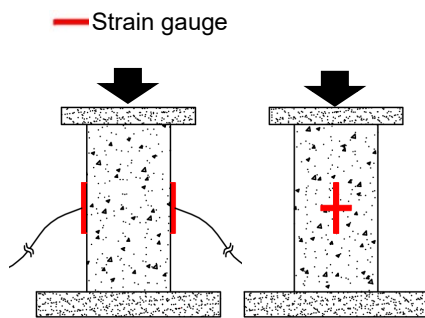


Fig. 3 Experimental setup of cylinder specimen

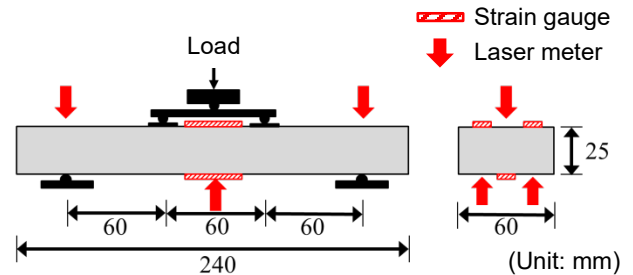


Fig. 4 Experimental setup of beam specimen under static tests

3.3 Result discussions

3.3.1 Compressive deformation behaviors and ultimate strength

The results of static compressive tests are summarized in **Table 3**. It is found that both the compressive strength and Young's modulus increased with the curing age from 28 days to 90 days, whereas experienced a gentle decline from 90 days to 165 days, which is different from the general cognition. The reduction from 90 days to 165 days is more apparent in the compressive strength. This is because Young's modulus was calculated using the stable elastic domain of stress to strain curves, whereas the compressive strength is related to the cracking behaviors and failure pattern. The almost unchanged Young's modulus indicates that the development of compression mechanical properties has likely stabilized. Regarding compressive strength, except for the curing age, some factors, such as fiber distributions and inherent defects, are also important and may become dominant as hydration progresses with curing age. Due to the non-uniform distribution of fibers and the random nature of defects, the compressive strength exhibits moderate variations rather than a perfect monotonic relationship with curing age, as observed in **Table 3**. By jointly comparing with the trend of the compressive strength development within 28 days as reported by Kuwagaki et al. (2020), it can be stated that the compressive properties of UHPFRC may reach a stable status after curing for 28 days. If all the obtained compressive properties are averaged, the mean values of compressive strength and Young's modulus are 155.55 MPa and 38.86 GPa, which are approximate to conventional values of UHPFRC. The elastic modulus approximating to that of concrete makes it more compatible to the original structure in repairing (Brühwiler, 2016).

Table 3 Static compressive properties for different ages

Age (days)	Specimen No.	Comp. str. (MPa)	Ave. Comp. str. (MPa)	Standard deviation (MPa)	Young's modulus (GPa)	Ave. Young's modulus (GPa)	Standard deviation (GPa)	Poisson's ratio	Ave. Poisson's ratio	Standard deviation
28	C28-1	165.99	151.61	14.08	38.71	38.99	0.25	0.275	0.27	0.01
	C28-2	137.92			39.11			0.262		
	C28-3	153.92			39.17			0.268		
90	C90-1	156.05	168.37	10.88	39.84	39.27	0.56	0.254	0.26	0.01
	C90-2	176.64			39.26			0.267		
	C90-3	172.42			38.72			0.264		
165	C165-1	170.57	145.27	22.73	37.90	38.31	0.37	0.234	0.25	0.02
	C165-1	138.63			38.61			0.263		
	C165-1	126.59			38.43			0.259		

3.3.2 Flexural deformation behaviors under quasi-static conditions

Fig. 5 shows the flexural stress to midspan deflection relationships of the specimens tested at curing ages of 28 days, 90 days, and 165 days. The deflections shown in the figures are calculated by averaging the measured deflections from both sides of each specimen at the midspan and then subtracting the deflection from the rigid movements at the supports. One can observe a typical three-stage of deflection evolution including linear elastic, strain-hardening, and strain-softening. Unlike the curves of

ECC (Engineered Cementitious Composite) as reported by Suthiwarapirak et al. (2004), no apparent load ups and downs which manifest stress release and recovery can be observed in UHPFRC. This suggests that the load holding capacity provided by the steel fibers should be more effective than the PE or PVA fibers (Li et al., 1990). Finally, one of the distributed cracks turned into a localized crack accompanied by an overall load decay. Deflection softening is observed after the crack localization.

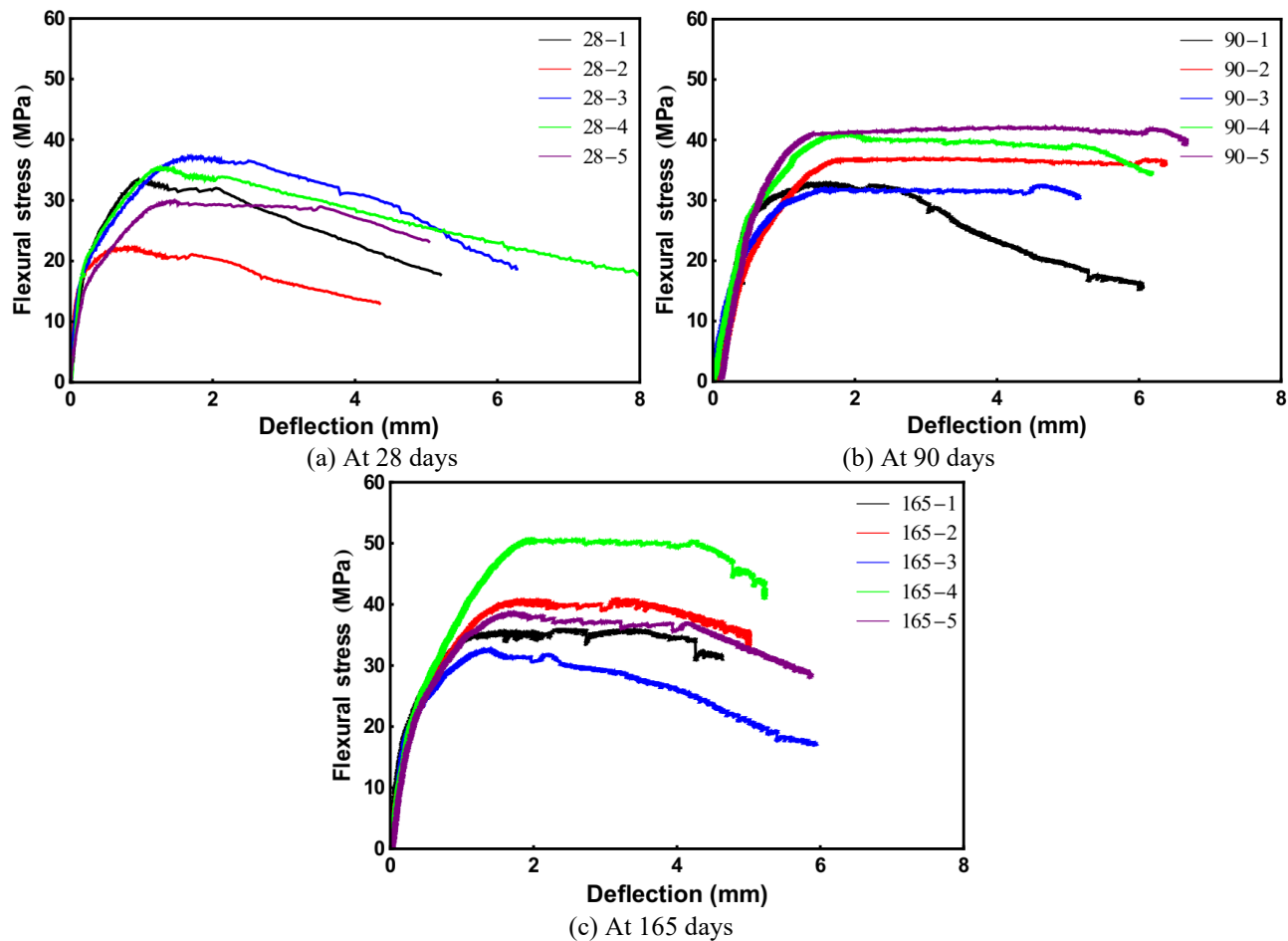


Fig. 5 Flexural stress vs. midspan deflection relations

3.3.3 Ultimate flexural strength under different loading speeds and at different curing ages

Table 4 summarizes the ultimate flexural load and the static flexural strengths of the UHPFRC beams under the three employed loading speeds at different ages. The static flexural strength was calculated by the elastic flexural beam formulation using the specimen dimensions measured at the fracture location after failure. The results of five specimens under one condition are averaged considering the specimen variance. In terms of the quasi-static flexural test results at different curing ages, it is found that the averaged ultimate flexural strength increases with the curing age from 30.42 MPa at 28 days, to 37.07 MPa at 90 days, and 39.76 MPa at 165 days. In addition, from the results of different loading speeds, one can observe a hardening effect due to a high strain rate. The averaged flexural strengths were 30.42 MPa, 39.44 MPa, and 36.24 MPa under the loading speeds of 0.1

mm/min, 60 mm/min, and 400 mm/min, respectively. As the ultimate flexural strength is also affected by other factors, such as fiber distribution and inherent defects, the strain rate effect may not be the dominant factor for about seven times loading speed increasing from 60 mm/min to 400 mm/min. Hence, for this variation of loading speed, a contradictory trend was observed. Actually, according to the general knowledge about the strain rate effect on cement-based materials (Habel and Gauvreau, 2008), the three loading speeds may be divided into two groups, i.e. quasi-static (0.1 mm/min) and quasi-dynamic (60 mm/min and 400 mm/min). As a result, it is reasonable to state that a higher loading speed generates a higher flexural load capacity.

Table 4 Flexural strengths under different loading speeds and at different ages

Age (days)	Load speed (mm/min)	Specimen No.	Flexural load (kN)		Standard deviation (kN)	Flexural str. (MPa)		Standard deviation (MPa)
			Each	Ave.		Each	Ave.	
28	0.1	S28-1	7.78	7.34	1.342	33.45	30.42	5.259
		S28-2	5.19			22.18		
		S28-3	8.67			33.94		
		S28-4	7.02			28.13		
		S28-5	8.06			34.41		
90	0.1	S90-1	6.84	7.72	0.934	32.81	37.07	4.482
		S90-2	7.69			36.92		
		S90-3	6.76			32.47		
		S90-4	8.54			41.01		
		S90-5	8.78			42.12		
165	0.1	S165-1	7.49	8.28	1.422	35.93	39.76	6.817
		S165-2	8.53			40.95		
		S165-3	6.8			32.64		
		S165-4	10.55			50.616		
		S165-5	8.05			38.64		
45	400	S45-1	8.89	8.25	0.922	37.71	36.24	5.297
		S45-2	6.76			26.94		
		S45-3	8.89			39.34		
		S45-4	8.3			37.44		
		S45-5	8.4			39.78		
48	60	S48-1	11.03	9.23	2.033	44.29	39.44	8.147
		S48-2	5.74			25.1		
		S48-3	9.7			42.05		
		S48-4	9.54			41.12		
		S48-5	10.12			44.61		

3.3.4 Static failure characteristics

Fig. 6 shows the two side views and one bottom views of the failure crack patterns of all specimens tested under bending. One can observe that the failure crack pattern can be divided into three typical types which are one major crack in the pure bending range, one major crack near the edge of the pure bending range, and two major cracks in and at the edge of the pure bending range as shown in **Figs. 6(a)-(c)**. All the images were taken using acetone to visualize the fine cracks. Focusing on the major cracks, it is found that the cracking paths exhibit a lot of twists and turns vertically and transversely and can be significantly inclined even for cracks located in the pure bent range. This may be due to the inertial effect included during crack propagation, thereby different crack tip field of stress and displacements are observed. In terms of the fiber distribution at the mouth of the major cracks after fracture, it is found that most of steel fibers are approximately horizontally oriented. This might be caused by a wall effect close to the boundaries as well as a fiber sink phenomenon. Thus, it is stated that the assumption of 3-dimensional random fiber distribution which is normally employed in simulating fiber reinforced concretes should be inappropriate for UHPFRC. Besides, fiber pullout is identified as the dominant failure characteristic as almost no fiber rupture can be observed.

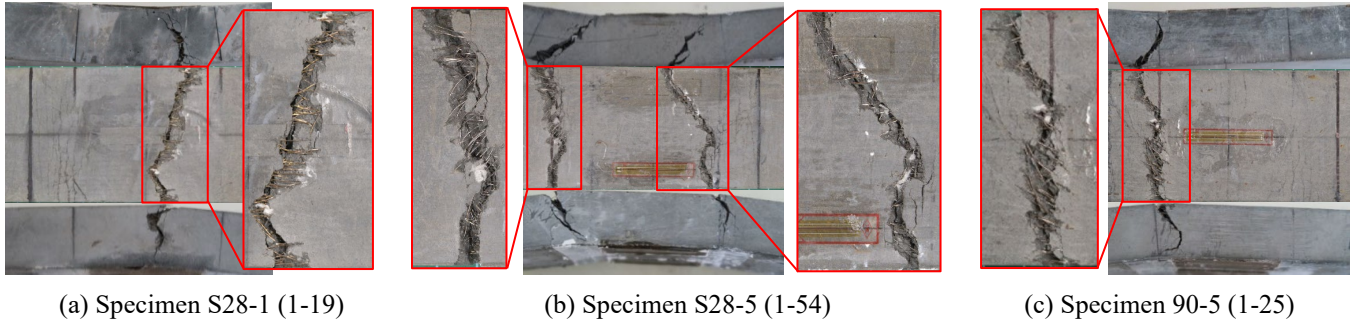
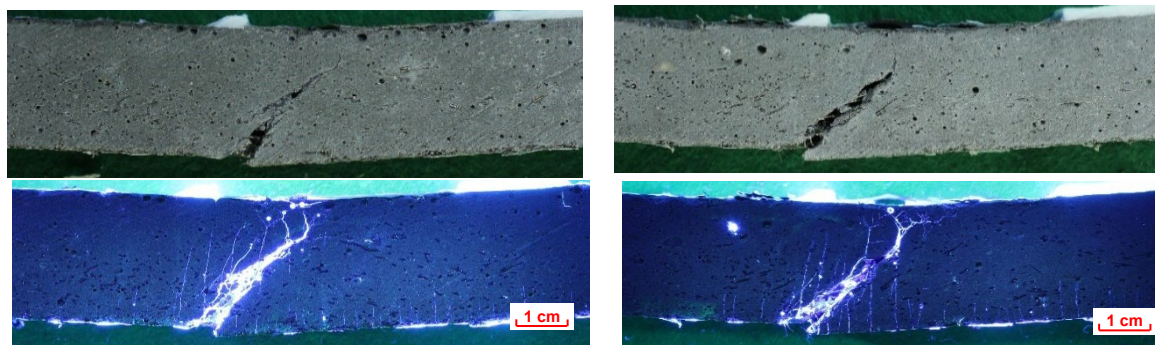


Fig. 6 Typical failure crack pattern of statically tested beams

In addition, one specimen (S28-1) with an approximate average load capacity of specimens tested at 28 days were cut longitudinally into three equal parts to investigate the internal cracks. **Fig. 7** shows the image of the cross sections obtained and the corresponding fluorescence image. Unlike the major cracks, all the multiple fine cracks are vertically. Except for the cracks adjacent to the major crack, no fine crack surpasses the middle thickness, which is identical to our observations in large-scale tests on UHPFRC-steel composite structures (Ma et al., 2021; Deng et al., 2022). Both these two observations demonstrate the excellent load redistribution capability of cracked UHPFRC. As the tested specimens are scheduled to be more comprehensively investigated by non-destructive testing techniques to understand the mechanical characteristics, only one specimen was cut in this study.



(a) Left 1/3 longitudinal section (b) Right 1/3 longitudinal section
Fig. 7 Failure crack pattern on cross sections of specimen S28-1 from cutting

4 FATIGUE FLEXURAL TESTS AND RESULT DISCUSSIONS

4.1 Fatigue flexural tests

The flexural fatigue tests started at 49 days were conducted under load control conditions. As it was reported that the degree of hydration reaction which reflects the mechanical development reaches 0.96 and 0.99 respectively after 28 and 90 days, the properties of UHPFRC may be regarded to be stable during the fatigue tests (Al-Azzawi and Karihaloo, 2017). Nevertheless, from the results of static tests, it may state that the loading speed should have some effect on the flexural strengths. To avoid this effect, a sinusoidal cyclic load with a 3 Hz of frequency was exploited in all fatigue tests to be approximate to the loading frequency on real bridge structures. Correspondingly, the static mechanical properties obtained under 60 mm/min were referred to determine loading ranges of fatigue tests. The ratio of maximum flexural stress to the static flexural strength is defined as the fatigue stress level, S . In order to construct the S-N relation, fatigue tests were conducted under at least four fatigue stress levels. To avoid any impact and slip of the specimens during tests, the minimum flexural stress which has a ratio of 0.2 with respect to the static flexural strength was set for all specimens. The fatigue tests were started from a fatigue stress level equaling 0.9 which is normally employed as the highest stress level for fatigue tests. Based on the fatigue test results of the previous fatigue stress level, the next fatigue stress level was determined to obtain an S-N relation with a range as wide as possible. The determined fatigue stress levels and the number of specimens for each fatigue stress level are shown in **Table 5**. In the first cycle, before the cyclic fatigue loading, a monotonic load was applied to the designed maximum stress level in about one min gradually. Fatigue loading was terminated either due to the occurrence of fatigue failure or once the runout cycles, i.e. two million cycles, were reached.

In terms of the runout specimens, static flexural tests were subsequently conducted up to failure to obtain the post-fatigue static load capacity which may explain why no fatigue failure occurred. As for each fatigue stress level, if it starts with more than 3 consecutive specimens which can sustain the runout cycles, no more specimens will be tested under this level, and fatigue tests

will be advanced under a higher fatigue stress level. As shown in **Table 5**, two groups of specimens were tested under a 0.925 stress level, nevertheless, the upper limit of the fatigue load range is different. This is because the latter group (F0.925_m) was tested at 165 days, correspondingly, the fatigue load range was modified using the static tests conducted at the same age.

Table 5 Number of specimens for each fatigue stress level

Name	Stress level	Max. load (kN)	Specimen number
F0.95	0.95	8.7	9
F0.925	0.925	8.5	2
F0.9	0.9	8.3	8
F0.85	0.85	7.8	3
F0.925_m	0.925	9.5	6

The loading condition and data acquisition system of the fatigue tests are shown in **Fig. 8**. The laser displacement meters were set to be the same as the static flexural tests. Similar to the static flexural tests, the compressive strain on the top surface of specimens at midspan was measured by two strain gauges with a length of 30 mm, whereas a π -shape displacement transducer with a length of 100 mm was attached to the bottom surface of the specimens at midspan instead to measure the deformation with the gauge length. Thus, both maximum compressive and tensile deformations were recorded. Two video cameras were set on both sides of the specimens to detect the temporal damage evolution together with regular visual observations. During fatigue loading, all measurements were recorded continuously at a frequency of 100 Hz which is more than 30 times the load frequency to obtain enough data points for one cycle. In addition, as shown in **Fig. 9**, two magnetic stoppers were mounted on the base of the loading machine at both ends of the specimens to restrain the longitudinal rigid movement of specimens during repetitive loading. A microscope (Dino-Lite Premier 500x) which has a magnification factor of 500x was employed to measure the widths and numbers of cracks on the bottom surface.

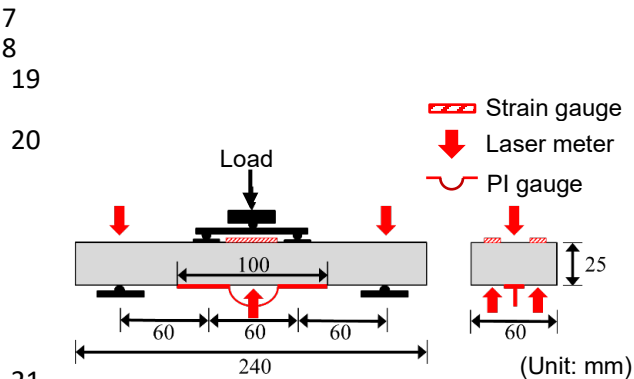


Fig. 8 Experimental setup of beam specimen under fatigue tests



Fig. 9 Image of the experimental setup

4.2 Result discussions

The fatigue test results of 28 UHPFRC specimens under five flexural fatigue stress levels are presented in this section. The fatigue stress ratio to the number of cycles to failure, i.e. S-N relationship, is constructed. The evolution of damage under flexural fatigue is discussed in terms of midspan deflection, midspan compressive strain, and crack mouth opening displacement (CMOD). Finally, the crack patterns and the number of cracks on the specimens after failure are illustrated to discuss the multiple cracking characteristics of UHPFRC.

4.2.1 Fatigue stress-life relations

The experimental fatigue life and the flexural fatigue stress level of all specimens are plotted on a semilogarithmic scale together with the fitting S-N relation as shown in **Fig. 10(a)**. The arrows indicate the specimens which can sustain two million cycles without failure. The relationship between the maximum flexural fatigue stress (σ_{max}) in MPa and fatigue life (N_u) in cycles can be represented by a straight line and expressed:

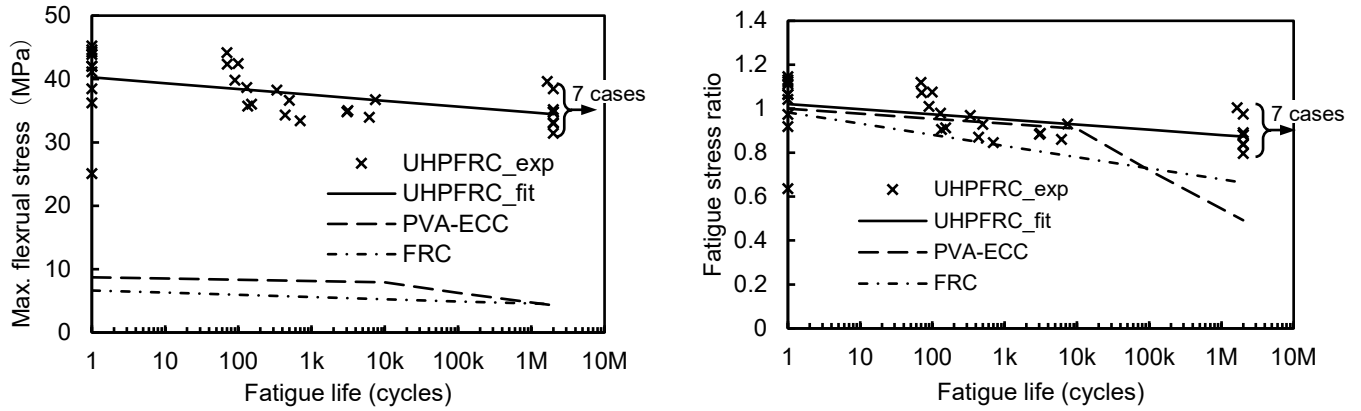
$$\sigma_{max} = 40.72 - 1.019 \log_{10}(N_u) \quad (1)$$

Besides, the normalized S-N relations of UHPFRC are shown in **Fig. 10(b)**, where the fatigue stress is divided by the static flexural strength. To facilitate the comparison with the other widely exploited fiber-reinforced composites, **Fig. 10(b)** also includes the S-N relations of fiber-reinforced concrete (FRC) as well as Engineered Cementitious Composites (ECC) with polyethylene (PE) and polyvinyl alcohol (PVA) fibers as reported by Suthiwarapirak et al. (2004). Unlike the ECCs, the UHPFRC exhibits a typical linear S-N relation similar to the FRC as well as other cementitious materials including concrete and polymer cement mortar (PCM). Nevertheless, UHPFRC exhibits a more gentle slope of curve than the other materials regardless of the fatigue stress level, which manifesting the material's superior fatigue resistance. This advantage of UHPFRC can be even more remarkable if the absolute strength is considered. Similarly, the fatigue stress ratio to fatigue life relationship is expressed in a format of the logarithmic function as:

$$S = 1.021 - 0.0234 \log_{10}(N_u) \quad (2)$$

Correspondingly, the fatigue endurance limit is 0.87. In addition, it is interesting to note that the fatigue life of UHPFRC is very sensitive to the fatigue stress level. Even though 28 specimens were tested under five fatigue load levels varying in a very narrow range with only a 15% difference, it is still difficult to obtain experimental data covering the full range of fatigue life. Only one data was obtained between ten thousand cycles and two million cycles. It seems that if the UHPFRC specimen can survive after ten thousand cycles, it can withstand that load permanently. Extending to engineering applications, one UHPFRC

1 structure may be regarded as highly durable if no apparent damage is detected after the early age operation. Further
 2 investigations are required to uncover this unique observation and consolidate this conjecture.



(a) Maximum stress vs. Fatigue life relation (b) Fatigue stress ratio vs. Fatigue life relation
Fig. 10 S-N relations

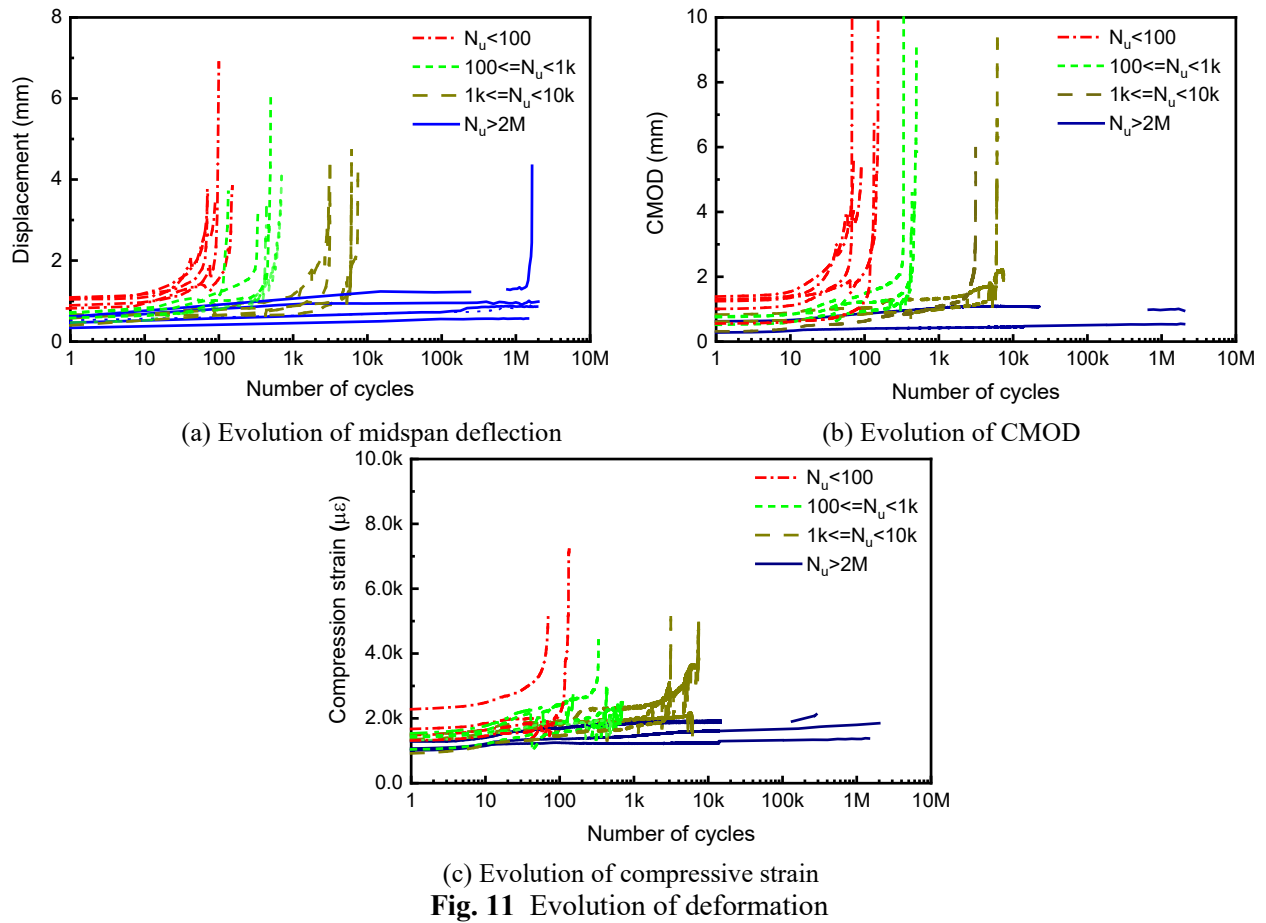
4.2.2 Fatigue deformation characteristics

8 The midspan deflection, the deformation on the tensile side, and the strain on the compressive side are employed to investigate
 9 the fatigue damage evolution. **Fig. 11(a)** shows the evolutions of the midspan deflection with the number of cycles. As the
 10 fatigue flexural stresses for all employed levels are not so different, no fatigue ratio is shown. It is found that the deflection
 11 increases steadily with the number of loading cycles, whereas the displacement development from the first cycle to the
 12 accelerated rising domain is very limited. According to the visual observation, multiple fine cracks were generated after the
 13 first cycle of loading even for the runout specimens, which demonstrates the excellent resistance-holding capacity of the steel
 14 fibers. Following the steady but slow-growing range, one can observe a sudden increase in the deflection, which indicates the
 15 final fatigue failure. To facilitate investigation, the displacement evolution curves are grouped according to their fatigue life
 16 instead of the fatigue ratios. It is clearly noticed that the specimen with shorter fatigue life normally has a larger first cycle
 17 displacement indicating a more significant damage caused in the initial cycle. This also means that superior to the flexural
 18 stress the midspan deflection or the structural deformation may have a more definite relationship with the fatigue life. More
 19 specifically, the averaged first cycle deflections of the specimens with fatigue life shorter than 100 cycles and longer than two
 20 million cycles are 1.06 mm and 0.49 mm, respectively. In terms of the midspan deflection evolution, the increment is quite
 21 limited with a maximum value of less than 0.2 mm among all the specimens. As the fatigue life exhibits an apparent dependence
 22 on the first cycle deformation, their relationships will be discussed in more details in the later sections.

23 In order to examine the multiple cracking and crack localization processes, the CMODs against the loading cycles are shown
 24 in **Fig. 11(b)** for the groups of different fatigue life. As illustrated in **Fig. 12**, the CMOD is calculated by subtracting the product

of the cracking strain and length (i.e. 100 mm) from the elongation measured using a Pi-gauge over the length. Similar to the evolutions of midspan deflection, the CMODs increase very slowly in the steady growth stage. These observations clearly demonstrate the damage distribution capability of UHPFRC due to the initiation and propagation of the multiple fine cracks. After the steady growth stage occupied by the fine cracks, a crack localization of UHPFRC that took place within a 100 mm length at the midspan was detected as manifested by a rapid increase of the total CMOD.

The compressive strain measured on the top surface of specimens is plotted against the number of cycles in **Fig. 11(c)**. Before the final failure, it is noticed that the compressive strain of many specimens experienced many drops with much more significant magnitudes than those exhibited in the deflection and CMOD evolutions. This may be caused by the fact that a fine crack that initiated from outside of the 30 mm length at the midspan developed into the critical major crack. In the following sections, the cracking behaviors will be discussed in detail to understand this unique observation.



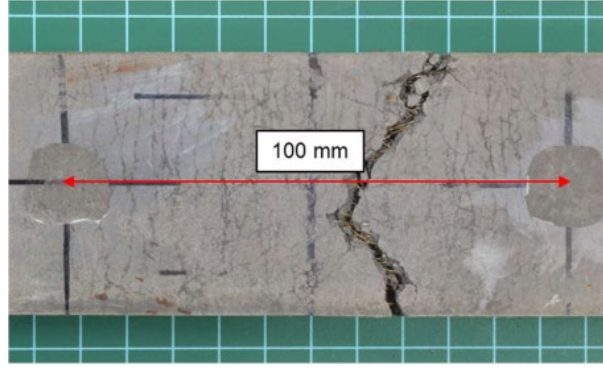


Fig. 12 Scheme of crack investigation

From the above indicators of the fatigue deformation evolution and comparing the corresponding fatigue performance of some other fiber-reinforced cementitious as presented by Suthiwarapirak et al. (2004), it is found that even though the UHPFRC exhibited a multiple cracking stage which determines the deformation evolutions similar to the ECCs, the magnitude, and speed of UHPFRC's deformation evolutions do not highly depend on the fatigue stress level or the deformation in the first cycle. More specifically, the increase of deformation or damage in the steady growth stage of UHPFRC is not as apparent as that of ECCs regardless of the fatigue stress level. Besides, due to the multiple cracking behaviors, the UHPFRC can sustain more damage than FRC until fatigue failure as the evolutions of midspan deflection and total CMODs were smaller than those of FRC.

4.2.3 1st cycle deformation behaviors and fatigue life

According to the deformation evolutions, it is interestingly noted that the fatigue life exhibited a dependence on the deformation or damage after the first cycle of loading. Thus, the relationships of the first cycle deformation behaviors are investigated. **Figs. 13-15** show the first cycle middle span deflection, elongation on the tensile surface, and compressive strain to flexural stress relations for specimens with fatigue life in the four ranges, where specimens are named using the fatigue stress level and their loading sequence. For example, F0.925-6 indicates that the specimen is the 6th one tested under a 0.925 Fatigue stress level. The total elongation measured by the π -gauge is employed instead of the CMOD excluding elastic deformation to provide the whole tensile behaviors. Comparing the four groups of curves, one can observe some similarities and differences. The elastic stiffness and cracking strength of all specimens are similar. Nevertheless, the slope change after cracking is more apparent in the curves of specimens with shorter life. Correspondingly, the extent of entering the strain-hardening domain and the final deflection exhibit an inverse correlation to the fatigue life of specimens. As the fatigue life of each specimen can be regarded as the cycles occupied by the displacement growth in the strain-hardening domain, the specimens which enter the strain-

hardening domain to greater extent after the first cycle and have a flatter strain-hardening domain tend to have a shorter fatigue life. In other words, the deformation behaviors exhibited in the 1st cycle may provide some hints for the fatigue life.

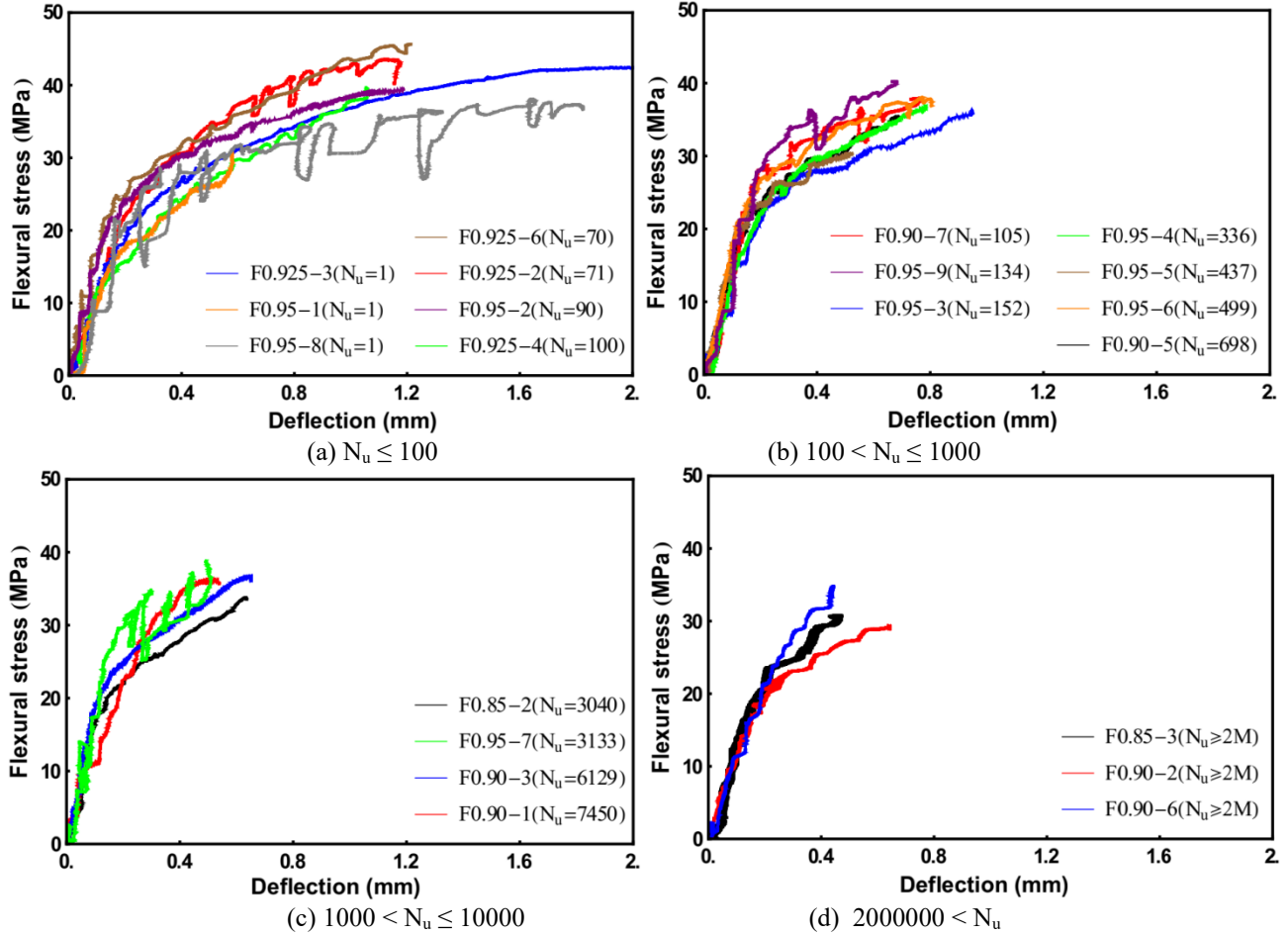
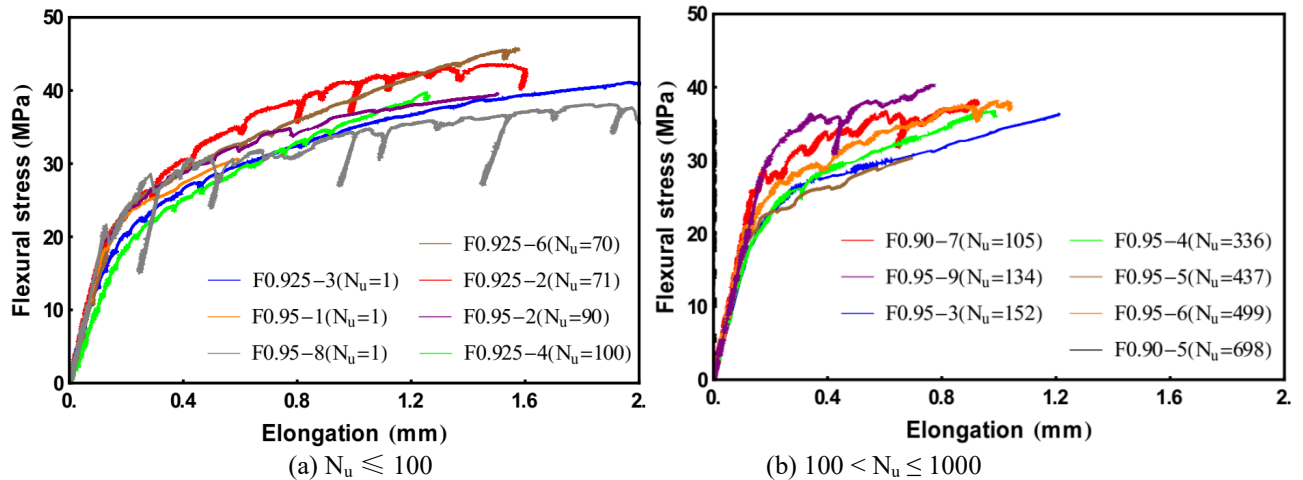
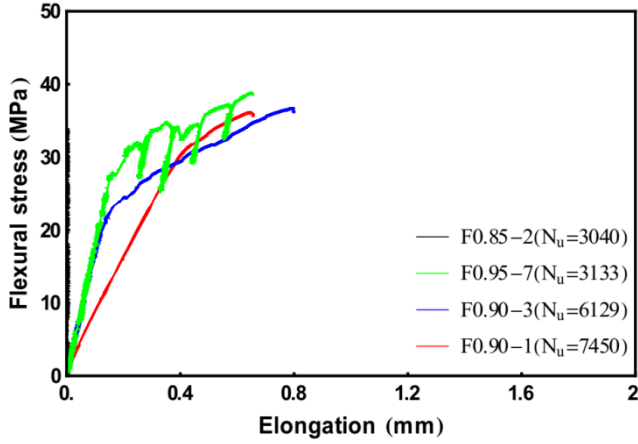
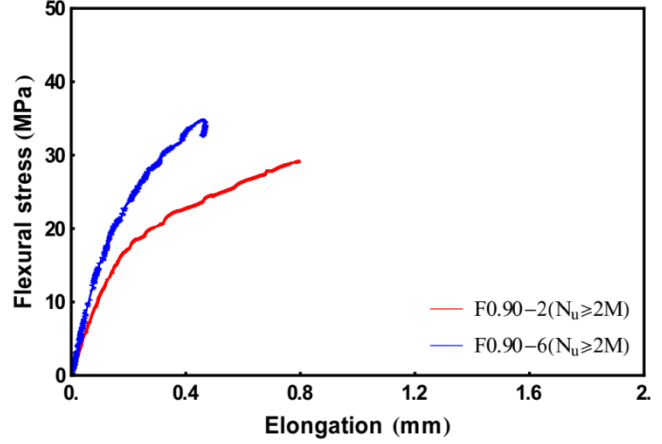


Fig. 13 First cycle of flexural stress vs. deflection relations



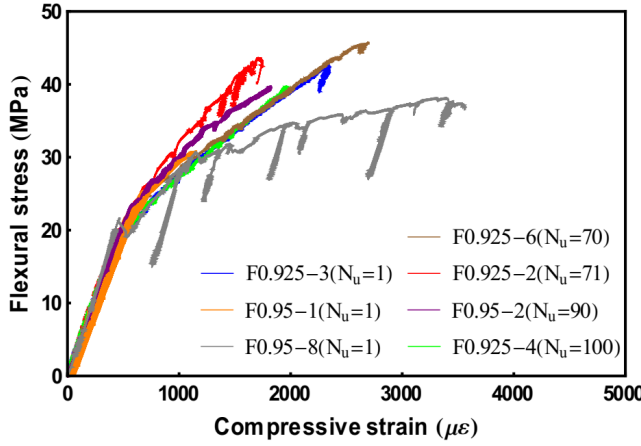


(c) $1000 < N_u \leq 10000$

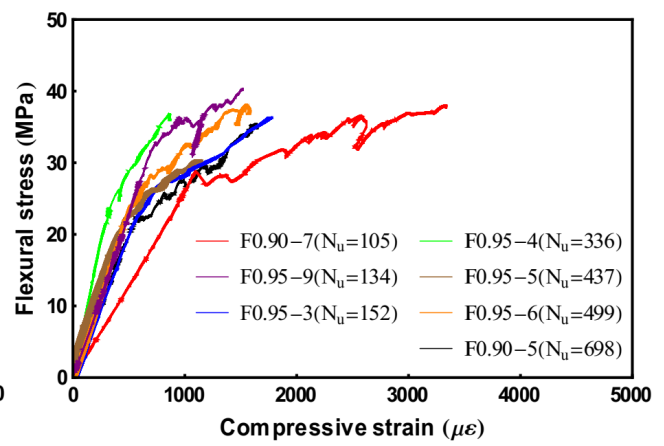


(d) $2000000 < N_u$

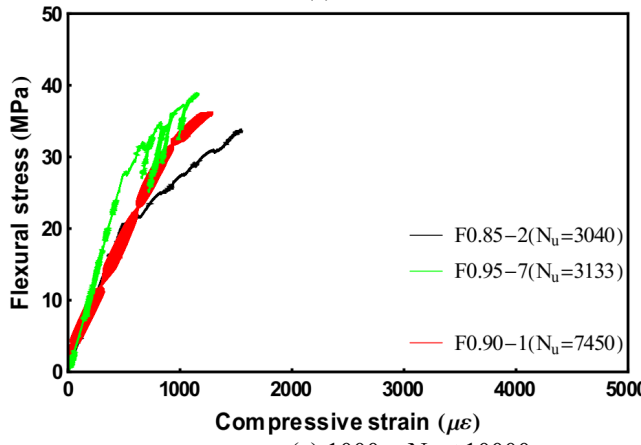
Fig. 14 First cycle of flexural stress vs. tensile elongation relations



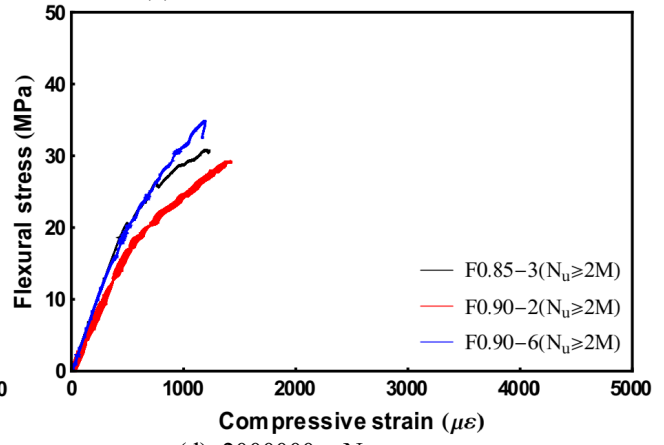
(a) $N_u \leq 100$



(b) $100 < N_u \leq 1000$



(c) $1000 < N_u \leq 10000$



(d) $2000000 < N_u$

Fig. 15 First cycle of flexural stress vs. compressive strain relations

Moreover, the relationships of the first cycle midspan deflection, total elongation, and compressive strain against the fatigue life are given in **Fig. 16**, respectively. It is noticed that all the experimental data points can be classified into two groups which are specimens with fatigue life shorter than 10,000 cycles and more than 2 million cycles. If the data points with fatigue life

varying in 1~10,000 and 1,000~2,000,000 cycles are exploited for fitting, separately, two straight lines can be obtained as presented in the three figures. In terms of a second straight line, the slope is much smaller than that of the first line and almost horizontally oriented, which means that there exists a threshold value for the occurrence of the fatigue failure. In other words, fatigue failure of UHPFRC under a certain stress level occurs only if the fatigue load can induce a deformation larger than the threshold value. Specifically, the threshold values are 0.51mm, 0.645mm, and 872 $\mu\epsilon$, respectively, for the first cycles of midspan deflection, total elongation, and compressive strain.

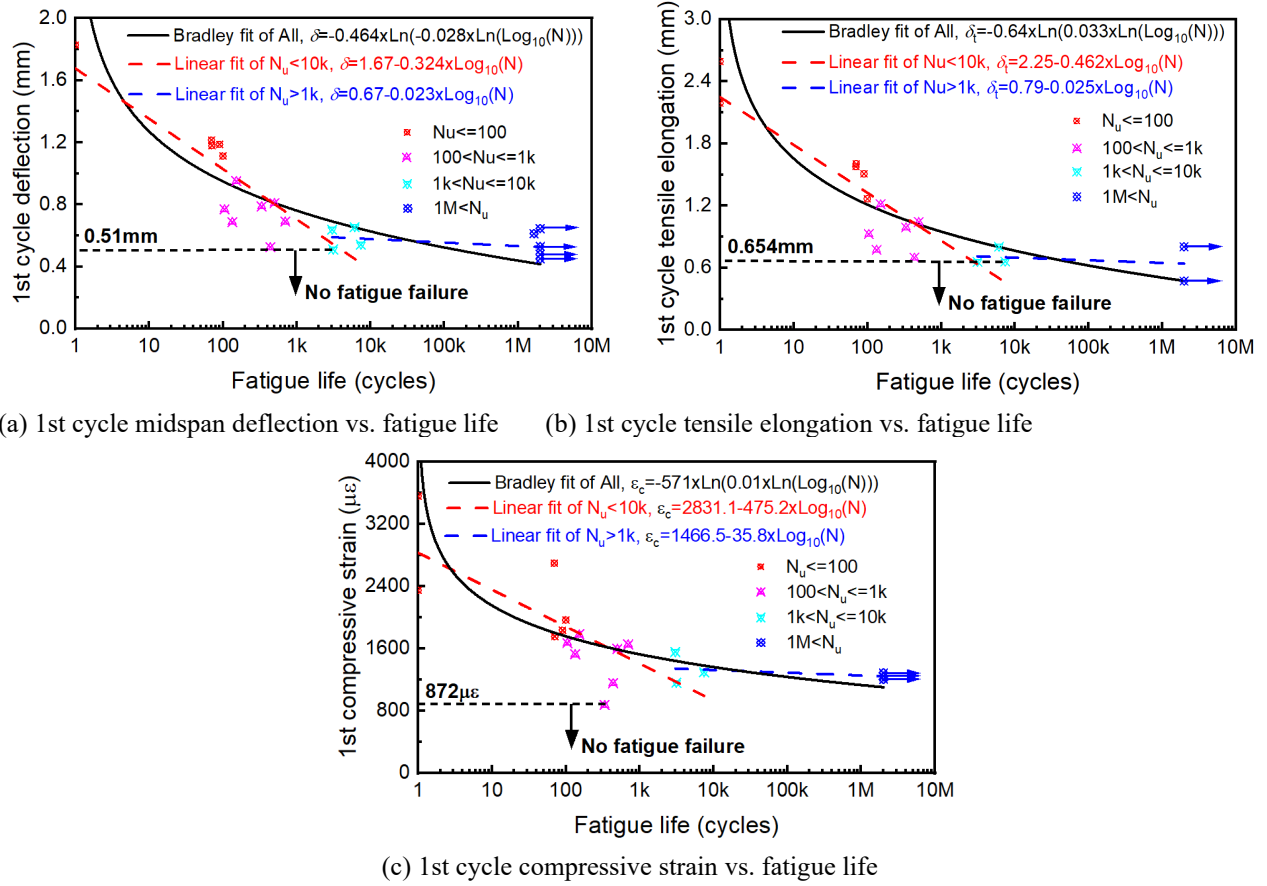


Fig. 16 Relations between first cycle deformation characteristics and fatigue life

4.2.4 Post-fatigue static strength of runout specimens

Static tests were conducted on the specimens which successfully sustained two million cycles. **Table 6** summarized the flexural strength obtained from the post-fatigue static tests as well as the upper limit fatigue flexural stress of the runout specimens. The flexural strength and fatigue stress were calculated using the measured dimensions at the location of the critical crack. A remarkable variation is observed in the obtained post-fatigue static flexural strength. It is also noticed that the averaged post-fatigue flexural strength is 58.35 MPa, which is much higher than the referenced static flexural strength of 39.44 MPa. This is

considered to be the differences between specimens related to the variation of fiber content and distribution. Besides, the ratios between the maximum flexural stress and the post-fatigue static flexural strength are presented in the fourth column of **Table 6** as well. It is found that even though the average value is about 0.599, the ratio can reach up to 0.783, which means that the fatigue endurance limit should be higher than 0.783. Compared to the 0.492, 0.588, and 0.663 fatigue endurance limits for PVA-ECC, PE-ECC, and FRC, respectively, as presented by Suthiwarapirak et al. (2004), this high ratio demonstrates the excellent fatigue performance of UHPFRC.

Table 6 Post-fatigue static flexural tests

Specimen number	Max. flexural str. (MPa)		Post-fatigue flexural str. (MPa)		Stress ratio	
	Each	Ave.	Each	Ave.	Each	Ave.
F0.925-1	35.17	33.84	44.93	58.35	0.783	0.599
F0.9-2	33.01		68.96		0.479	
F0.9-6	34.82		64.22		0.542	
F0.9-8	34.77		66.48		0.523	
F0.85-3	31.44		47.16		0.667	

To facilitate the investigation of the relations between static strength and the loading conditions, the flexural strengths of all tested specimens are plotted against the testing age in **Fig. 17**. The growth of flexural strength with the curing age and the strengthening effect of high-speed loading can be clearly observed. Besides, the post-fatigue static flexural strengths exhibiting a significant variance are basically higher than the normal static flexural strengths. In many cases, the post-fatigue strengths can be even much higher than maximum flexural strengths obtained under all the employed loading conditions, which implies that the strength of specimens may have been increased by some factors. For example, a heating up of specimen due to direct sunlight and the repetitive load may lead to further hydration resulting in some extra mechanical development. To uncover this phenomenon and provide concrete explanations, more comprehensive investigations are required.

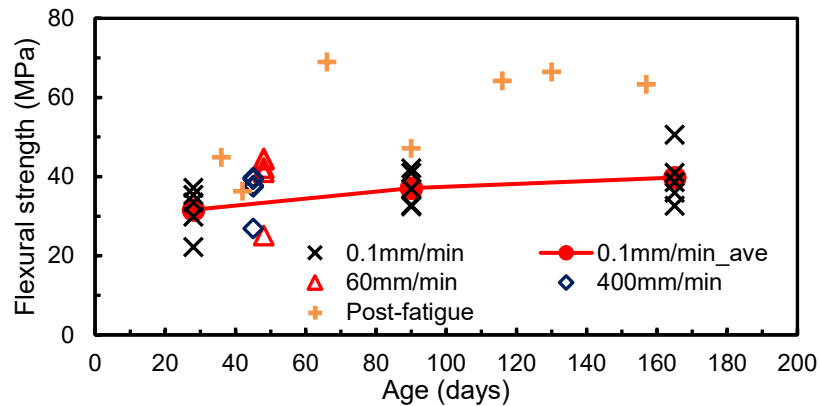
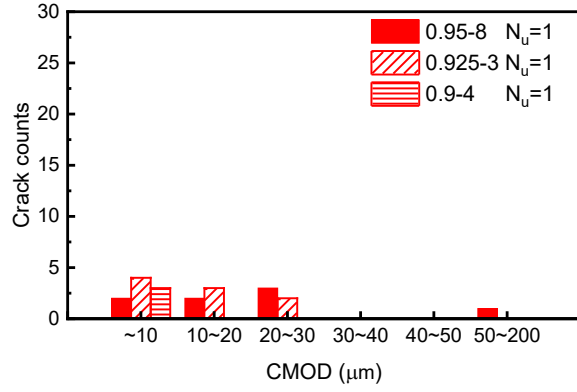


Fig. 17 Static flexural strength of specimens tested at different ages, under different loading speeds, and after fatigue tests

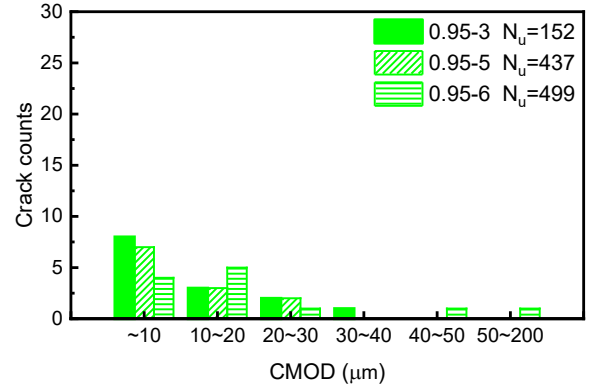
4.2.5 Fatigue failure characteristics

From the bottom surface of the specimens which endured the fatigue tests, the number of fine cracks is counted and their widths are measured using a microscope (Dino-Lite Premier 500x) along a 100mm length center line as illustrated in **Fig. 12**. Correspondingly, the distributions of the number of cracks against the crack width ranges are given in **Figs. 17(a)-(d)** for the specimens with fatigue life varying in the four employed ranges. It is found that the crack width is almost limited to 50 μ m or below which is even more narrow than that of ECCs (Qiu and Yang, 2017) and most of the minor cracks have a width of less than 20 μ m for all four groups. According to the results of penetration tests, Aldea et al. (1999) concluded that the intrusive of chloride ions and the corresponding detrimental effect can be neglected if the crack width is less than 200 μ m. Thus, it may be demonstrated that UHPFRC even after cracking can act as an anti-corrosion coating enhancing the structural durability. Besides, with such fine crack width, UHPFRC with an about 0.25 water-to-cement ratio is expected to restart the hydration in the presence of water leading to a self-healing characteristic and significant mechanical recovery (Qian et al., 2009; Qian et al., 2010; Yang et al., 2009). In fatigue studies on UHPFRC-steel composite decks under both dry and wet conditions, the performance enhancement due to the self-healing of cracked UHPFRC has been reported by Ma. (2022) and Mitamura et al. (2021). This feature also benefits the life extension capability of UHPFRC in structural rehabilitation.

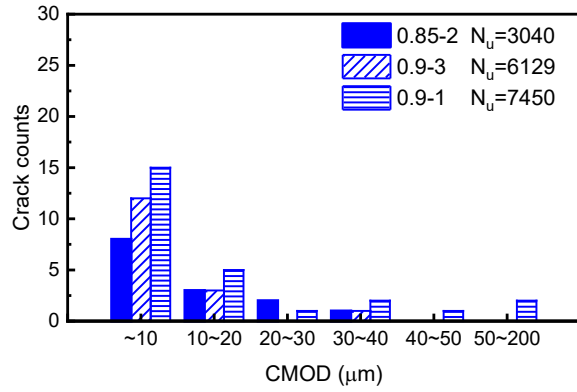
Fig. 19 shows the relations between the distribution characteristics of the multiple cracks and the fatigue life together with the corresponding functions obtained from linear regression. It is noticed that the average crack spacing of all specimens varies from 2.5 mm to 11 mm with only one exception, which is consistent with the observation of statically tested specimens. Besides, the specimens which withstand more loading cycles tend to have more multiple fine cracks. This observation may be understood as follows. As discussed in the previous sections, the specimens which possess higher strength and longer strain-hardening domain exhibit a superior load redistribution capacity. Consequently, more multiple fine cracks tend to be formed under a successively increasing load. In brief, the stronger specimens can have more cracks. As for the tested specimens in this study, as the upper limits of the fatigue load are not so different, it may be stated that the specimens exhibiting longer fatigue life are the stronger ones and can have more cracks.



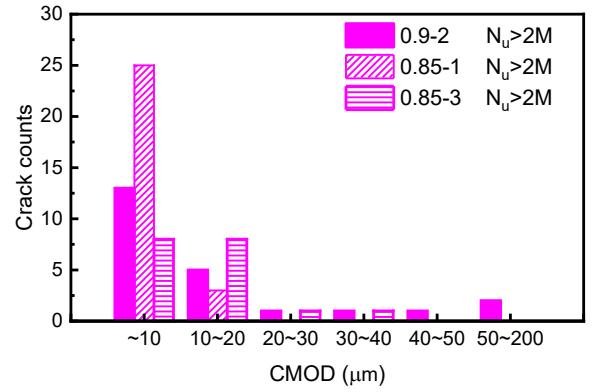
(a) $N_u \leq 100$



(b) $100 < N_u \leq 1000$

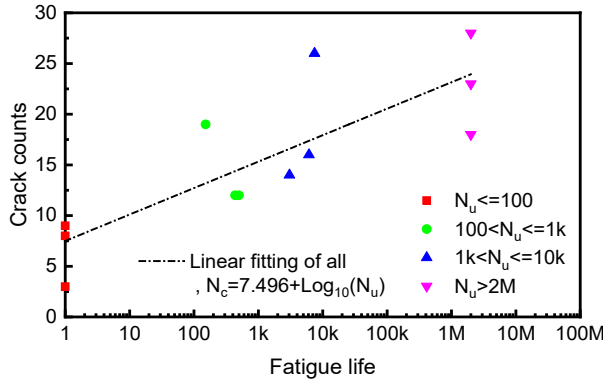


(c) $1000 < N_u \leq 10000$

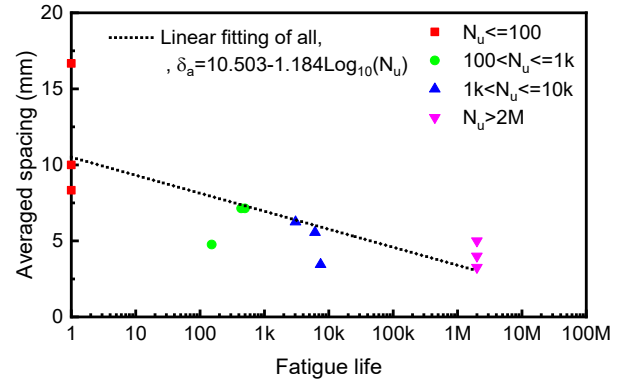


(d) $2000000 < N_u$

Fig. 18 Number of cracks vs. fatigue life relations



(a) Crack counts to fatigue life relation



(b) Averaged crack spacing to fatigue life relation

Fig. 19 Multiple cracks distribution

5 CONCLUSIONS

In this study, the flexural characteristics of UHPFRC were investigated using four-point static and fatigue flexural tests. The main conclusions are as follows:

1 1. The flexural properties of UHPFRC continue to improve even after 165 days. The multiple cracking and strain-hardening
2 behavior provide UHPFRC with remarkable ductility, evidenced by a midspan deflection to half-span ratio of 1.5/90 at ultimate
3 flexural strength.

4 2. Under high-speed loading, a strengthening effect may be observed. Therefore, the commonly employed loading frequency
5 of up to 10 Hz for concrete tests might be inappropriate for UHPFRC.

6 3. Based on the fatigue flexural tests, a linear S-N relation with a 0.87 fatigue endurance limit was established on a semi-
7 logarithmic scale. For the runout specimens, the maximum fatigue load to post-fatigue residual capacity ratio can be as high as
8 0.783. These findings demonstrate the excellent durability of UHPFRC.

9 4. According to the fatigue life, the specimens can be classified into two groups: those with a lifespan shorter than 10,000
10 cycles and those exceeding two million cycles. Regardless of the fatigue life, the increments in midspan deflection evolution
11 of all specimens were very limited until failure. Additionally, the fatigue life exhibited a clear relationship with the deformation
12 in the first loading cycle. There appears to be a threshold value of deformation for the occurrence of fatigue failure, which
13 warrants more comprehensive investigation.

14 5. The cracking investigation indicated that more fine cracks formed in specimens with longer fatigue life. Except for the major
15 cracks, the width of multiple cracks and the crack spacing were less than 50 μm and 10 mm, respectively, demonstrating the
16 superior load redistribution of cracked UHPFRC. Additionally, it was observed that only fiber pullout, and no fiber rupture,
17 occurred along the major cracks.

19 **CONFLICT OF INTEREST**

20 None.

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